Research on Electric and Magnetic Asymmetry of Linear and Arc Motors

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Introduction

The main disadvantage of linear and arc induction motors greatly limiting their wider usage in modern technologies is the longitudinal and transverse edge effect [1]. Due to their influence on the three – phase motors there is formed inner electric and magnetic asymmetry. Although such type of motors are integrated into the symmetric network or are supplied power from the symmetric three – phase source, but in reality they are dissymmetrical electromechanical energy converters. The mentioned above asymmetry aggravates the calculation of the characteristics of such converters and complicates the implementation of microprocessors and computers to be applied for their control [2].

The techniques for calculation linear, arc and liquid metal magnet – hydrodynamic pumps [3, 4] were compiled and applied long ago. Their inner asymmetry is not taken into consideration but the assumption is made, that the mentioned converters have to be alternating – current supply from the symmetric three – phase current source. The influence of the edges effects on such technologies is evaluated by the brought in resistances of the resultant scheme as well as by the coefficients of correction. The data results of the experiments accumulated by some authors [5, 6, 7] state that by powering these motors from the symmetric source of the voltage, the obtained calculation might give diversity of 30% varying from the results received after having applied methods of calculation.

The objective of the research is to investigate the magnetic field structure of linear and arc motors to be as inner asymmetry in order to be able to predict possible means and measures of its compensation.

Data of experimental motors

Some dipolar (p = 1,0) linear and arc motors have been experimentally researched under a special testing – bench with three non – ferrous secondary elements of variable width: the width of the first element is 64 mm, the second is 104 mm, the third is 104 mm, but with transversal gaps. Three – phase dipolar inductors differed by the number of windings and the cross – section of the wire, they have been alternating – current supply by symmetric voltage sources of 50 Hz and 400 Hz frequency.

The diagram for connecting the windings of a three – phase inductor when the number of slots per pole and phase is q = 1,0, is presented in Fig. 1.

![Fig.1. The scheme for connecting inductor windings: a – a is a transversal axis of the inductor; b – is an open magnetic core; c – is direction of movement of the secondary element](image)

During the time of experimenting there were measured phase voltages \( U_u, U_w, U_v \) and currents \( I_u, I_w, I_v \) active
power P, starting power F and distribution of magnetic flux density \(B_0\) within the air gap along the longitudinal axis L of the inductor. Then there were calculated complete power S, relative power \(F/P\) and \(F/S\) and currents of inverse sequence, using the technique of symmetric components. The results of tests and calculations are presented in Table 1, the curves of magnetic flux density are presented in Fig. 2.

![Fig. 2. Magnetic flux density distribution within the air gap of the motor when \(U = 200\ V, 400\ Hz\) and the secondary element I: 1 – without the means of compensation; 2 – with a shortly connected loop](image)

The notes of Table 1 include the following markings: WMC – is a test without using the means of compensation; SC – is symmetrizing of electric circuit by applying capacitors; SCL – are tests with a shortly connected loop.

The data of the tests indicate that the currents of the inductor phases signify themselves by electric asymmetry creating currents of the inverse sequence, the value of which may comprise up to 10 – 30\% of the direct sequence currents. When carrying out test No.7 (see Table 1.), to each phase of the inductor there were connected capacitors of uneven capacity in series. This measure completely deletes the currents of the inverse sequence but it is unable to compensate the component of a fluctuating magnetic field.

**Magnetic field simulation**

In order to have a more vivid view on the inner asymmetry of linear and arc motors it is necessary to carry out the magnetic field simulation within the whole magnetic circuit of the motor.

In a general case according to the law of energy exchange the electromagnetic force of the motor may be calculated in the following way:

\[
F_{el} = -\frac{dW_m}{dx};
\]  

where \(W_m\) – is magnetic field energy in the motor; \(x\) – is a longitudinal coordinate of the motor.

On the other side the electromagnetic force of the motor also depends on the angle \(\theta\) of the inductor turn in respect to the axis perpendicular to its active zone:

\[
F_{el} = k_wBA\cos(\psi - \cos\theta);
\]  

where \(k_w\) – is the coefficient of the inductor winding; \(B\) – is average value of the magnetic flux; \(A\) – is linear current load of the inductor; \(\psi\) – is the angle of differences of phases between the electromotive force of the secondary element and of the current vectors.

(1) and (2) expressions indicate that electromagnetic force depends not only on the magnetic field energy created in the motor but on the magnetic flux density distribution character in the air gap of the motor. That is why in order to provide the optimum sine distribution of the flux and reduce hazardous influence of the edges effects it is required to investigate the structure of the magnetic field of the motor.

In simulating magnetic field it is useful to make use of the generalized value – magnetic vector potential:

\[
A = iA_x + jA_y + kA_z;
\]  

where \(i, j, k\) – are the orts of Descartes system of coordinates; \(A_x, A_y, A_z\) – are on the axes \(x, y, z\) of vector potential projection.

The correspondence with two dimensional magnetic field flux density \(B\) is based on the following dependence:

\[
B = \text{rot} A = i\frac{\partial A_x}{\partial y} - j\frac{\partial A_y}{\partial x};
\]  

**Table 1. Data of the tests and calculations**

<table>
<thead>
<tr>
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<tr>
<td>1</td>
<td>220 [V], 50 [Hz]</td>
<td>I</td>
<td>I, 0,99</td>
<td>51,4</td>
<td>14,2</td>
<td>19,2</td>
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<tr>
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<td></td>
<td>II</td>
<td>3,80, 3,12</td>
<td>48,3</td>
<td>14,0</td>
<td>16,4</td>
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</tr>
<tr>
<td>3</td>
<td></td>
<td>III</td>
<td>3,22, 2,61</td>
<td>54,5</td>
<td>18,4</td>
<td>15,2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>200 [V], 400 [Hz]</td>
<td>I</td>
<td>4,81, 3,75</td>
<td>10,2</td>
<td>4,14</td>
<td>15,9</td>
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</tr>
<tr>
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<td>9,10</td>
<td>4,14</td>
<td>12,1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>III</td>
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<td>7,38</td>
<td>11,7</td>
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</tr>
<tr>
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<td></td>
<td>I</td>
<td>5,60, 5,60</td>
<td>11,5</td>
<td>5,76</td>
<td>0</td>
<td>SC</td>
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<td>I</td>
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<td>II</td>
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<td>4,44</td>
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<td></td>
<td>III</td>
<td>6,10, 5,02</td>
<td>13,2</td>
<td>7,62</td>
<td>11,7</td>
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</tr>
</tbody>
</table>
where $A_z$ is normal component of the vector potential.

For the magnetic field simulation of motors there have been used the software package Maxwell SV 9.0 of the company „Ansoft“. The software has been compiled by means of finite elements by attaching to certain geometric forms on the computer their names and peculiarities. Fig. 3 present the models of magnetic circuit finite elements of linear and arc motors.

![Fig. 3. Finite elements models of linear a) and arc b) motor with two active zones](image)

There was investigated the distribution of magnetic flux lines in both types of motors under different substances of inductor windings and the secondary element as well as by changing the frequency of inductor current and the size of the air gap. The results of simulation have been presented in Fig. 4 and Fig. 5.

![Fig. 4. Distribution of magnetic flux lines in the linear motor, when the secondary element is ferromagnetic and air gap is 2 mm](image)

![Fig. 5. Distribution of magnetic flux lines in the arc motor, when the substance of the secondary element is copper](image)

The principal of the compensation of the component of edge effect and fluctuating magnetic field component in such type of motors is based on the compilation of the additional linkage at the ends of an open magnetic cores.

**Conclusions**

1. The experimental and simulation results indicate that inner asymmetry of three phase linear and arc motors powered from the sources of symmetric voltage mainly depend on the number of terminals, type of winding, frequency on the powered voltage and substance of the secondary element as well as on the design.

2. The amount of the electric asymmetry is evaluated by the coefficient of asymmetry, which is expressed by the ratio of reverse and linear sequence of the complex amplitudes of inductor phase currents.

3. When trying to reduce inner asymmetry of motors controlled by the valve converters in the canals of separate phases of converter there are required the controllers of current and voltage of variable parameters and structure.

4. When compiling optimum control systems of linear and arc motors, the application of all the measures of asymmetry compensation mentioned in this article has to be based on technology standards and economy level.

**References**


2. **Karaliunas B., Matkevicius E.** Calculation of the Parameters of Linear Electric Drive // Trans Tech

Issues concerning the experimental investigation on linear and arc motors as well as their usage in mechatronic system are discussed. The research proved that due to an open magnetic circuit in such type of motors there is formed inner electric and magnetic asymmetry, exhibiting itself by causing different currents in the phases of an inductor and providing unequal concentration of magnetic field in conformity with the longitudinal and transversal axes of the motor. The qualitative expression of such a type of asymmetry is regarded as longitudinal and transverse edge effects phenomenon limiting the application possibilities of such kind of motors.

Experimentally there have been carried out the research on three dipolar linear and arc motors with secondary elements of different width. The results of the experimental research were provided, when motors were alternating – current supply from symmetric voltage sources of 50 Hz and 400 Hz frequency. For magnetic field simulation of a linear and arc motor there has been used software package Maxwell SV 9.0 worked out by „Ansoft“ company. There has also been investigated the distribution of magnetic flux lines in the motor under the condition of different substances used for the secondary element and by changing the frequency of the current of the inductor and the size of air gap. The results of the experimental research and modeling prove the structure of the magnetic field of motors to be a rather complicated one, for the analysis of which there are required new and sufficiently accurate mathematical models. The means and measures for edges effects and asymmetry compensation are being discussed. Il. 5, bibl. 7 (in English; summaries in English, Russian and Lithuanian).


Рассматриваются вопросы экспериментального исследования линейных и дуговых двигателей, а также вопросы применения их в махтотронных системах. Показано, что из-за открытой магнитной цепи в такого рода двигателях образуется внутренняя электрическая и магнитная асимметрия, которая проявляется разными токами в фазах индуктора и неоднинаковой концентрацией магнитного поля по продольной и поперечной оси двигателя. Качественным выражением такой асимметрии являются продольный и поперечный краевые эффекты, которые ограничивают применение этих двигателей в махтотронных системах.

Экспериментально были исследованы три двухполюсные линейные и дуговые двигатели с вторичными элементами разной ширины. Представлены результаты экспериментального исследования, когда двигатели были запитаны из симметричных источников напряжений частотой 50 Гц и 400 Гц. Для моделирования магнитного поля линейного и дугового двигателя был применен программный пакет Maxwell SV 9.0 фирмы „Ansoft“. Исследовалось распределение магнитных силовых линий в двигателе при изменении частоты питающих токов индуктора, величины воздушного зазора и при разных материалах вторичного элемента. Результаты экспериментального исследования и моделирования свидетельствуют о сложной структуре магнитного поля, для анализа которой требуются новые и достаточно точные математические модели. Рассмотрены также способы и средства компенсации асимметрии и краевых эффектов. Ил. 5, библ. 7 (на английском языке; рефераты на английском, русском и литовском языках).


Nagrinėjami tiesiagiai ir lankinių variklių eksperimentinio tyrimo ir jų panaudojimo mechatroninėse sistemos klausimai. Parodyta, kad dėl atviro magnetinės grandinės tokio tipo varikliuose susiformuoja vidinė elektrinė ir magnetinė asimetrija, pasireiškianti skirtingomis srovėmis induktorius fazėse ir nevienoda magnetinio lauko koncentracija pagal variklio išsipalvęs ir skersinę ašį. Tokios asimetrinės kokybinė ir išraiška yra išsirūninės ir skersinis kraštų efektai, ribojantys šių variklių taikymą mechatroninėse sistemose.

Eksperimentiškai buvo tiriami trys dvipolės tiesiagiai ir lankiniai varikliai su skirtino pločio antrinius elementus. Pateikti eksperimentinio tyrimo rezultatai, kai varikliai buvo maitinami iš 50 Hz ir 400 Hz dažnio simetriinių tarpusavio šaltinių. Tiesiagiai ir lankinio variklio magnetiniam laukui modeliuoti buvo naudojamas „Ansoft“ firmos programinis paketas „Maxwell SV 9.0“. Buvo tiriamas magnetinio srauto linijų pasiskirstymas variklyje, esant skirtinių antrinio elemento medžiagai bei keičiant induktorius srovės dažnį ir oro tarp dydį. Eksperimentinio tyrimo ir modeliavimo rezultatai buvoja apie sudėtingą magnetinio lauko struktūrą, kurią analizė ir reikalingi naudoti ir gana tikslūs matematiniai modeliai. Taip pat aptariamos kraštų efektų ir asimetrinio kompensavimo priemonės ir būdai. Il. 5, bibl. 7 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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